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ABSTRACT

The use of photovoltaic (PV) systems on buildings has increased in the last few decades due to decreasing price and growing concern about non-renewable energy usage. Photovoltaic technology provides renewable energy to utility grids while also reducing reliance on the grids. Several incentive, rebate and net metering programs help make PV systems more affordable. In the United States, homes account for 37% of all electricity use and 22% of all primary energy consumption. This significant impact on energy usage makes it necessary to shift toward more environmentally responsible sources of energy. Existing residential buildings can play a significant role in deploying photovoltaic technology. This study demonstrates a potential deployment of PV systems on housing in a northern climate where people usually believe that solar irradiation is insufficient to make PV systems feasible. The results show that, with available incentive programs and other system benefits, PV systems can compete with purchasing electricity from the grids. However, more incentive programs or the integration of PV systems into building skins could make the investment return more favorable.

1. INTRODUCTION

A key element of sustainable development in building construction is reducing the use of energy that depletes natural resources. For this purpose, renewable energy has been introduced to the building industry, but as of today, only a small fraction of world energy is produced from renewable sources. In the United States, solar energy accounts for only 1.2% of total energy consumption (Energy Information Administration, 2009). However, the use of photovoltaic systems in building has been on the rise in the last few decades due to its decreasing price and the growing concern over non-renewable energy usage. In the United States, as in many parts of the world, solar-electricity is a fast growing market. United States solar energy consumption grew around 10% each year from 2006 through 2008 (Energy Information Administration, 2009).

In 2008, the residential sector accounted for 22% of total energy consumed in the country (Energy Information Administration, 2007). The solar market in the residential sector was accelerated by the Federal Residential Renewable Energy Tax Credit, which grants a tax credit equal to 30% of the investment cost without a maximum amount until the end of 2016. Some states have also adopted renewable portfolio standard (RPS) regulations that set targets for increasing production of energy from renewable energy sources, such as solar, wind, geothermal and biogas. The RPS mechanism generally places a requirement for electric utility companies to produce or buy a specified fraction of their electricity from renewable energy sources. PV systems in residential buildings are considered electricity generators that can also sell their certified solar electricity back to the utility companies. The RPS mechanism also helps accelerate PV market growth in the residential sector because utility companies create various types of rebate and incentive programs to support the installation of solar electricity systems. As of 2009, more than half of states in the United States now have renewable portfolio standards (RPS) or renewable mandates.

This paper aims to demonstrate the available technology and tools that can be used to quantify the performance and economic benefits of PV systems in residential buildings in northern climates. A common misconception about the utilization of photovoltaic (PV) systems in northern climates is that they produce significantly less electricity than systems installed in areas closer to the equator. The northern climate is comprised of many cloudy days and a short daytime duration during a long cold winter. It is usually assumed that there is not enough sunshine to produce sufficient electricity to meet the demand and that, consequently, PV systems are not suitable for this kind of climate.

The solar map in Fig. 1 shows the daily average amount of solar insolation in kilowatt-hours that falls onto flat surfaces per square meter per day throughout the United States.

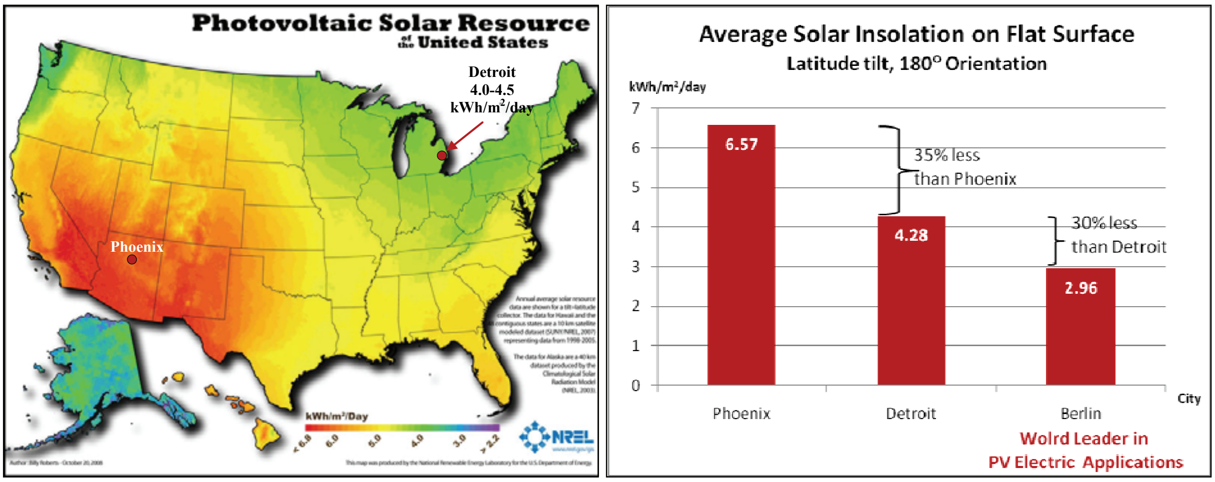

Figure 1: Solar map produced by the National Renewable Energy Laboratory (NREL) and bar graph showing solar insolation in Detroit, Michigan compared to other places as calculated by PVWATTS.

As can be seen in Fig. 1, areas in the north, for example Detroit, Michigan, have an average solar insolation falling onto south facing (180° orientation) and latitude tilt flat surfaces of approximately 4.0 to 4.5 kWh/m^2/day. Whereas, areas in the south, for example, Phoenix, Arizona, have an average solar insolation ranging from 5.5 to more than 6.8 kWh/m^2/day. This data might discourage the use of PV in northern climates based on the fact that the amount of solar insolation is at least 18% less than in areas of the southwestern United States. However, the successful use of PV systems depend on more than just the amount of solar insolation. The chart in Fig. 1 shows detailed calculation results of the solar insolation that falls onto flat surfaces tilt at the latitude angle facing a southern orientation in Phoenix, Detroit and Berlin, Germany. While areas in the northern United States receive around 35% less solar insolation compared to areas that are closer to the equator, the amount of solar insolation on flat surfaces is actually 30% more than in areas of northern Europe. Germany, which is a top world PV installer, accounting for almost half of all global PV system capacity, has only 2.96 kWh/m^2/day of solar radiation reaching flat surfaces. Other major cities in Europe for example, London in the UK, also receive about the same level of solar radiation as Germany. The utilization of PV systems tends to depend heavily on energy management rather than the availability of solar radiation (Wassmer and Warner, 2006). Moreover, PV panels produce more electricity when the panels are cool than when they are hot, making it is possible for PV systems to perform better in colder climates. Finally, direct light is not the only source for energy generation in PV systems. Indirect light or reflected light from clouds and the surroundings may also affect the efficiency of PV systems in areas without a great deal of sunshine and could result in better than expected performance.

1.1 Site and climate

The Fleming Creek housing development in the northeastern part of Ann Arbor, Michigan is selected as a case study. Ann Arbor is a small university-city in southeastern Michigan (Fig. 2). It is considered to be in climate zone 5A according to ASHRAE Standard 90.2-2007 Energy-Efficient Design of Low-Rise Residential Buildings (American Society of Heating Refrigerating and Air-Conditioning Engineers Inc., 2007). Climate zone 5A is classified as humid continental (warm summer). Fleming Creek's latitude and longitude are 42.22N and 83.75W. The weather is generally cold during the long winter with an average temperature of -5°C, and an average of 24°C in summer. The daily highest global horizontal solar radiation ranges from 200 Wh/m^2/h in winter to 780 Wh/m^2/h in summer. Sun shines on the southern face of a house all year (Fig. 3). The latitude tilt angle for a PV system in Ann Arbor is 42.2° from horizontal. The panel installed angle, however, can vary from the latitude angle by ± 15° with less than 5-6% in solar radiation reduction. For example, at latitude tilt 42.2°, the average solar radiation is 4.28 kWh/m^2/day while at 57.2°, it is 4.06 kWh/m^2/day and at 27.2°, it is 4.30 kWh/m^2/day.

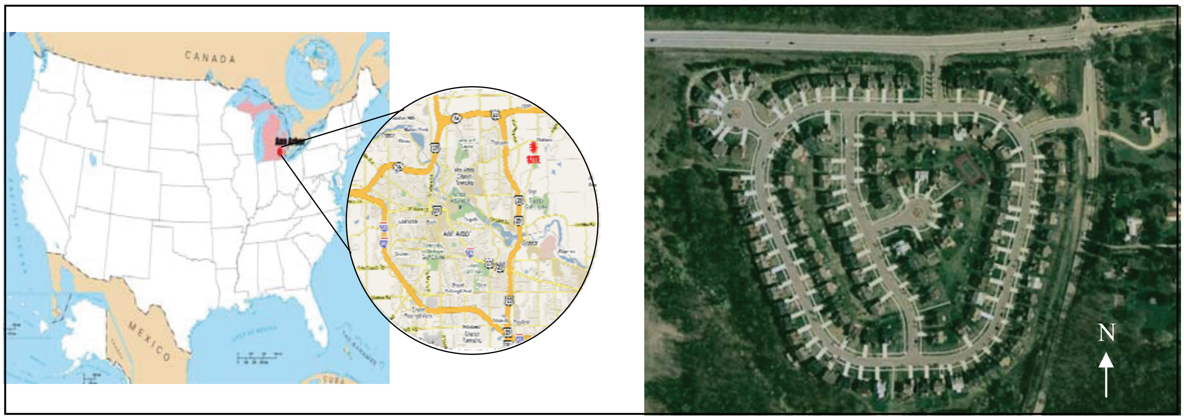

Figure 2: Study site location and orthophotograph from Google Maps

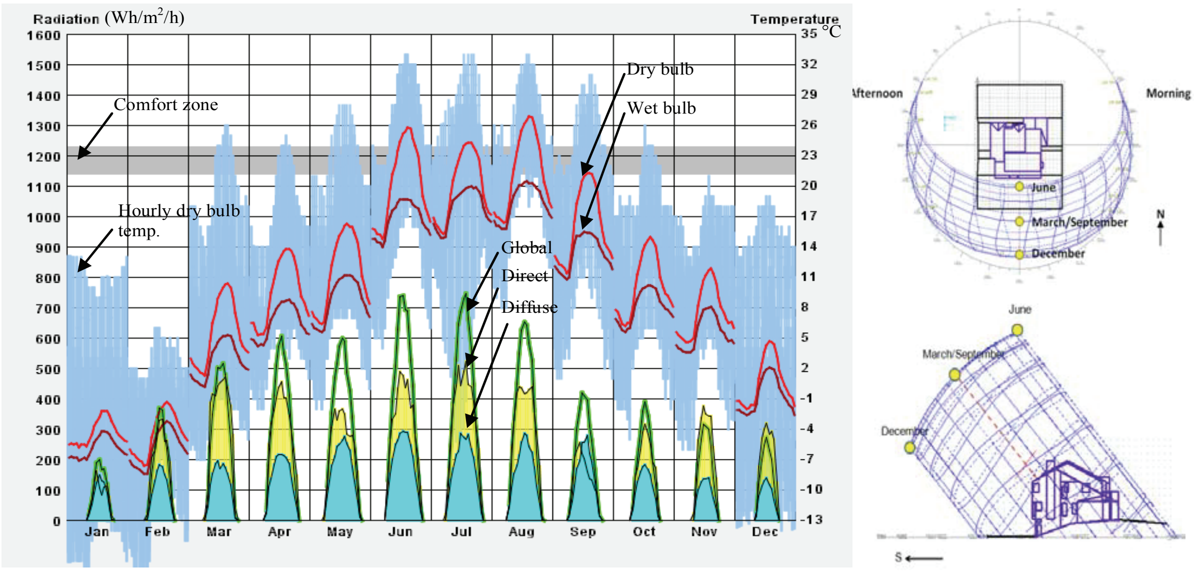

Figure 3: Climate plot from TMY 3 data for Ann Arbor, Michigan using Climate Consultant 4.0 and sun path diagram from Adobe Ecotect 5.6

1.2 Housing characteristics

In the northern hemisphere, the optimum orientation of PV panels is due south and the optimum slope of the PV panels is equal to the latitude at that location. Along with considering the orientation and slope of the PV panels, it is essential to consider if the PV panels will be shaded from the sun by trees or other buildings during the course of the day and seasons. However, in existing housing, optimum orientation of the PV may not be achievable due to the fact that houses are normally placed in various orientations in order to share central facilities (Fig. 4).

Constructed in the 1990s, Fleming Creek is a residential complex with 122 medium-sized detached houses. The house sizes range from 160-280 m^2 with three or four bedrooms per house. Roof areas range between 180-240 m^2. In this particular example, the front of the house orientation shared by the greatest number of houses is northeast, followed by northwest. Fig. 5 shows the relative amount of solar radiation received by PV oriented around the compass.

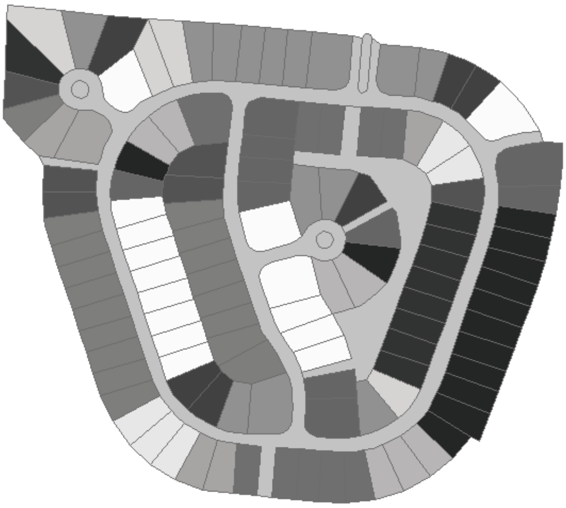

Figure 4: House orientation. Plots of the same color face about the same direction.

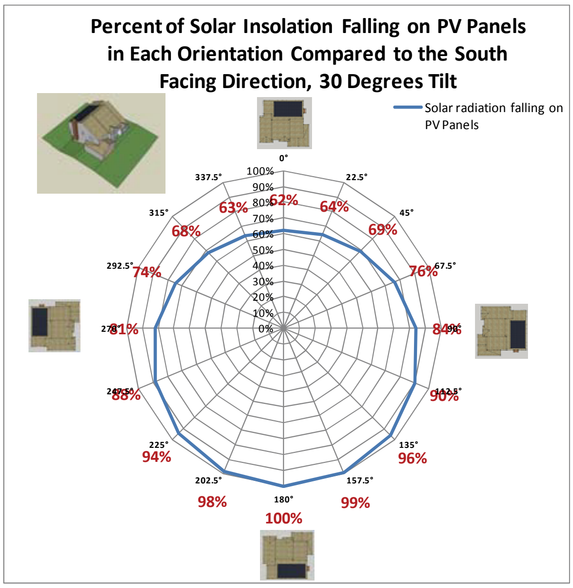

Figure 5: Amount of solar insolation falling onto a flat surface at 30° tilt angle in each direction compared to the southern orientation. Location: Detroit

Even though all the houses look similar, they differ in details. More than 14 designs exist in this housing development. For simplicity in the initial investigation, a Huron II house type with 255 m^2 of rooftop was selected as a representative because 30% of all the houses (40 of 122 units) are of this design and half of them face northeast.

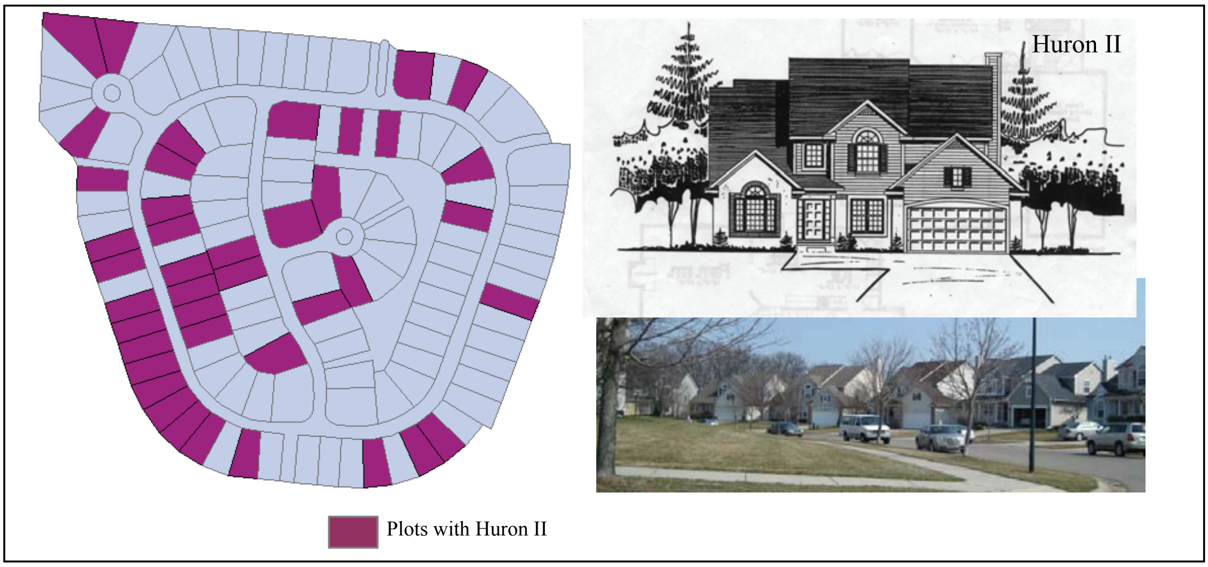

Figure 6: Huron II houses and their locations in Fleming Creek

2. METHODOLOGY

In this study the houses are first examined using ariel photographs and models in Google Sketchup Pro 7.1 to identify any major obstructions to solar radiation. Then, three main tools are used to quantify the amount of solar energy that can be captured during the course of one year and the amount of electricity that can be produced. These tools are Autodesk Ecotect 5.6, eQuest 3.6 and PVWATTS1.0. Economic analysis is then carried out using the price of PV and currently available incentives.

3. RESULT AND DISCUSSION

3.1 Obstructions from surroundings

There are no major obstructions in this housing development. Trees are not a problem and the house roofs are located high above the ground so that the shade created by each house does not interfere with the others.

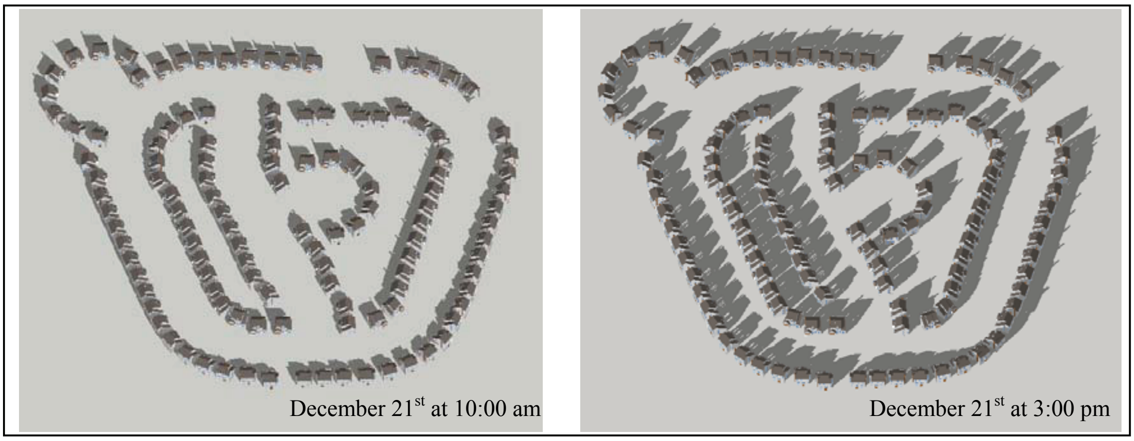

Figure 7: Shading in December

Figure 8: Historical satellite images of the site obtained from Google Earth

3.2 Electrical use characteristics of the typical house

Electrical consumption and solar radiation falling onto the roof of an east-facing house were simulated throughout the year using eQuest. According to the simulation the annual electric energy consumption of a typical house facing east is 42,111 kWh or 165 kWh/m^2. Ann Arbor is in the east north central region which has an average residential electricity consumption equal to 45.5 kWh/m^2 (Energy Information Administration, 2007). Medium and larger-sized houses, like those of Fleming Creek, use a great deal more energy than the average regional consumption. However, these houses also have ample roof area for the installation of PV systems. The graphs in Fig. 9 show electricity consumption throughout the average day in June and December compared to the electricity that can be produced from PV systems assuming 80% of the roof area is covered with PV panels and the panel effeciency is 15%. This anaysis shows that using electricity generated by PV systems can help offset peak energy demand during the day. The total electricity produced nearly covers the total electrcity used in the house.

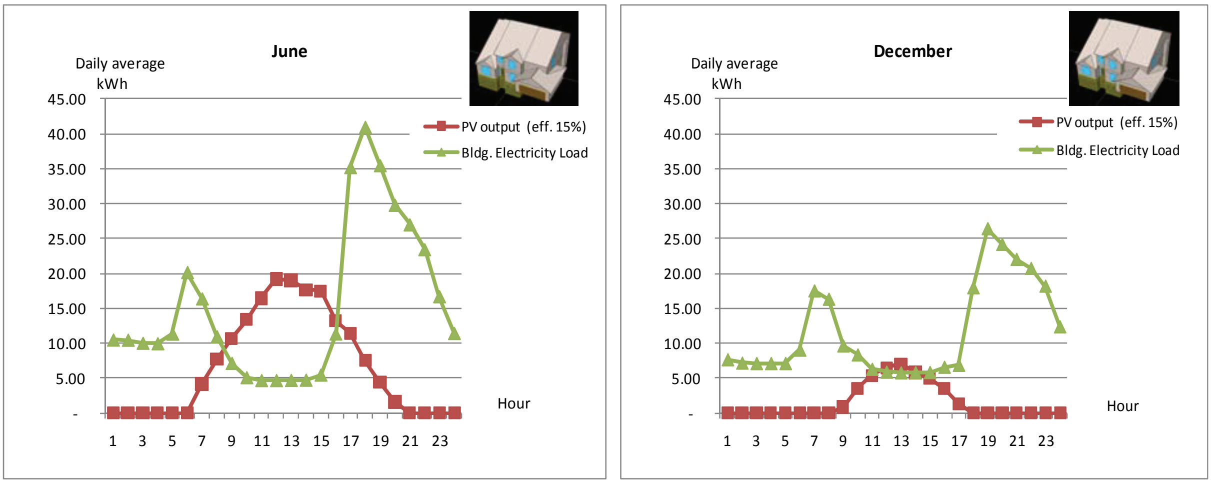

Figure 9: Graphs show daily electric consumption in a house and daily electricity produced from PV panels over the average day in June and December

3.3 Solar irradiation and total AC output results

Four types of commercial PV systems are selected and their characteristics were used in this study. Their characteristics are summarized in Table 1.

Table 1: Selected PV systems and their characteristics.

Brand	Uni-Solar SHR 17	BP-Solar BP 3170	Sanyo HIT Power N	Sunpower 210
				
Rated power (W)	17	170	210	210
Voltage at P_{max} (V)	9	36.6	41.3	33
Current at P_{max}(A)	1.9	4.8	5.09	4.36
Open-circuit Voltage (V_{oc})	13	43.6	50.9	46.2
Short circuit current(I_{sc})	2.4	5.2	5.57	5.3
Efficiency	6%	13.6%	16.7%	16.9%
Size	5"(12")x86.4"	31.1" x 62.5"	31.4" x 62.2"	31.4" x 61.4"
Warranty	product wanrranty: 5 years Power Output Warranty: 92% at 10 years 84% at 20 years 80% at 25 years	product wanrranty: 5 years Power Output Warranty: 93% at 12years 85% at 25years	product wanrranty: 5 years Power Output Warranty: 20 years	product wanrranty: 10 years Power Output Warranty: 25 years

Both the solar radiation falling on roofs oriented around the compass at a tilt angle of 30° from horizontal and the total output AC energy were computed using PVWATTS1.0. The TMY2 data for Detroit were used instead of Ann Arbor because it is the closest location for which data is available from the program. The PVWatts program calculates the solar radiation incident on the PV array and the PV cell temperature for each hour of the year from TMY2. The DC output energy is calculated from the PV system DC rating combined with solar irradiation and adjusted for the PV cell temperature (Menicucci, 1986). The output is then multiplied by the overall DC-to-AC derate factor of 0.77 to account for losses due to factors such as inverter efficiency, mismatch, wiring, dirt or shade. In this analysis, it is assumed that every house is able to find areas on its back roof to accommodate a PV system at 4.0 kW (DC). The results are shown in Table 2. The total output is as high as 458 MWh/year, or on average 3.75 MWh/house.

Table 2: Total energy output from Fleming Creek housing if every house installed a 4 kW PV system.

Roof orientation	Solar radiation (kWh/m^2/day)	AC Energy (kWh)	Efficiency (%)				No. of houses	Total output AC Energy (kWh)
			SHR 17 (0.13*2.2 m^2/panel) Installed area = 66 m^2	BP 3170 (1.6*0.8 m^2/panel) Installed area = 31 m^2	HIT Power N (1.6*0.8 m^2/panel) Installed area = 25.6 m^2	Sunpower 210 (1.6*0.8 m^2/panel) Installed area = 25.6 m^2		
0°	2.87	2,850	4.1%	8.8%	10.6%	10.6%	13	37,050
22.5°	2.95	2,947	4.1%	8.8%	10.7%	10.7%	5	14,735
45°	3.14	3,187	4.2%	9.0%	10.9%	10.9%	2	6,374
67.5°	3.39	3,502	4.3%	9.1%	11.1%	11.1%	16	56,032
90°	3.66	3,837	4.4%	9.3%	11.2%	11.2%	10	38,370
112.5°	3.81	4,013	4.4%	9.3%	11.3%	11.3%	13	52,169
135°	4.12	4,384	4.4%	9.4%	11.4%	11.4%	6	26,304
157.5°	4.25	4,533	4.4%	9.4%	11.4%	11.4%	1	4,533
180°	4.28	4,565	4.4%	9.4%	11.4%	11.4%	10	45,650
202.5°	4.22	4,489	4.4%	9.4%	11.4%	11.4%	4	17,956
225°	4.06	4,301	4.4%	9.4%	11.3%	11.3%	5	21,505
247.5°	3.84	4,033	4.4%	9.3%	11.2%	11.2%	18	72,594
270°	3.58	3,722	4.3%	9.2%	11.1%	11.1%	5	18,610
292.5°	3.31	3,395	4.3%	9.1%	11.0%	11.0%	9	30,555
315°	3.08	3,104	4.2%	8.9%	10.8%	10.8%	4	12,416
337.5°	2.92	2,903	4.1%	8.8%	10.6%	10.6%	11	2,903
						Total	**122**	**457,756**

Another way to calculate the DC output of a PV system is by calculating solar insolation on PV areas and multipling by its efficiency. The calculation from Ecotect shows that solar insolation received on rooftops could be as high as 11,000 MWh in total. If the efficiency of the PV systems is 10%, it can be implied that as much as 1,100 MWh of electricity can be produced. However, if every house installs PV systems only on their back roof with an area of 80 m^2 each, the total solar insolation falling onto those panels would be 2,800 MWh. Making the total electricity generated when PV systems are 10% efficient 280 MWh. This analysis was carried out by simulating a house in each direction, then multiplying those simulation results by the number of houses facing each direction. However, it is possible to carry out a simulation of the whole 122-house development in Ecotect. It has been found that when all houses were simulated using their real orientations, the total solar radiation falling onto roof surfaces is reduced by 15%. Therefore, the methodology of estimating total solar radiation by multiplying the number of houses in approximately each direction by the result from one house in each direction appears to overestimate the total insolation.

3.4 Economic analysis

If it is assumed that the cost of PV system installation is \$9/watt, then a 4.0 kW system would cost \$36,000. After the incentives of a 30% federal tax credit of the gross cost at installation and DTE's Solar Current program's upfront Recs payment of \$2.4/watt installed, the system cost is reduced to \$15,600 (\$3.9/watt). With a roof tilt angle of 30° the systems can produce electricity at 2,850 to 4,565 kWh/year depending on their orientations. Electricity production at 3,700 kWh/year is used in this analysis. The current price of electricity at the site is approximately \$0.11/kWh. With net metering available in Michigan, the electricity cost savings per year is \$407. For this study, it is assumed that the price of electricity escalates at 1.5%/year over the 30-year expected lifetime of the system. DTE's Solar Current program also provides an ongoing Recs payment of \$0.11/kWh for 20 years. The maintenance cost is assumed to be \$50/year (Perez et al., 2004), and an inverter will require replacement every 15 years at a cost of \$0.25/watt (Navigant Consulting Inc., 2006). Economic analysis shows that with the incentive programs currently available in Ann Arbor, installing standard PV systems is still not appealing in terms of internal rate of return and net present value (Fig. 10). However, if PV systems can be part of architectural materials, for example, if they can replace roofing that, in this case, needs to be replaced every 10 years at an average cost of \$11,000 for the entire roof, then the investment return could be favorable. For other PV system types, more incentives should be introduced to accelerate homeowner adoption.

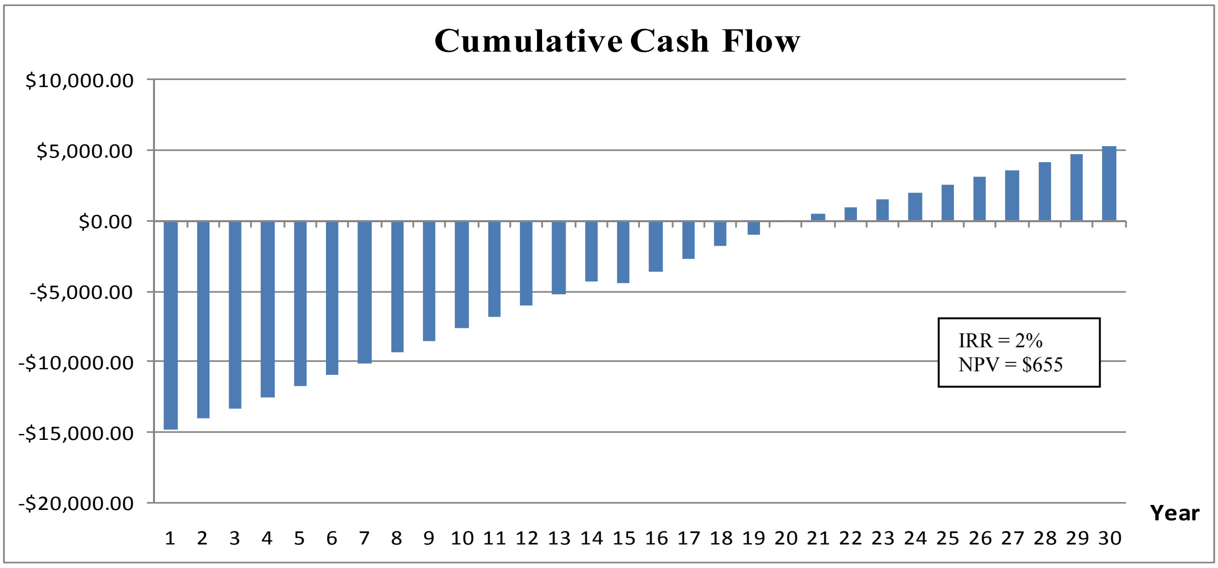

Figure 10: Cash flow of the 4.0 kW system after incentives

4. CONCLUSION

The earth receives a vast amount of energy from the sun in the form of solar radiation. If only 0.02% of the solar radiation falling on the earth surface is converted into usable energy, the energy demand of the entire world would be met. PV systems are considered one of the most environmental friendly power generation systems because during their lifetime they consume no additional energy beyond sunlight. Because they lack moving parts, they also work quietly. The use of PV systems in buildings has many benefits. The electricity produced from the systems, as shown in this study, provides direct economic benefit. If PV systems can be designed and installed as parts of building skins, investment payback time will be accelerated due to the elimination of traditional building skin material costs. Even though building skin materials made from PV systems are more expensive, the electricity production from these skins can offset their higher cost. Installing PV systems will qualify the owners for many available incentive programs based on their use of renewable energy. These programs are designed to encourage PV system installation by lowering investment costs. Indirect benefits from PV systems include reduced use of fossil fuels, thus reducing CO_2 emissions, and a positive influence on public perception that can generate higher property sale prices. Many homeowners will also appreciate the energy independence afforded by PV systems.

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